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Sonar range prediction models REPAS and REACT

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ABSTRACT (UNCLASSIFIED)

The range prediction models REPAS and REACT for passive and active sonars respectively, have been developed at FEL-TNO between 1986 and 1990 . These models and the propagation loss model ALMOST on which REPAS and REACT are based, are documented in this report.
The report describes also the way in which the reverberation is calculated, which is an important part of the REACT-model. A description is given of two modules, which calculate reverberation and target echo level as a function of time respectively. Afterwards time is converted to detection range for operational use.
Finally a method has also been included, for the determination of the threshold level for various detection situations, used in REPAS as well as REACT. With this method also the detection probability can be calculated versus detection range. Some examples of detection range prediction calculated by REPAS and REACT are presented.

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SAMENVATTING (ONGERUBRICEERD)

De afstandvoorspellingsmodellen REPAS en REACT voor achtereenvolgens passieve en actieve sonars zijn op FEL-TNO ontwikkeld, tussen 1986 en 1990. Deze modellen en het propagatieverliesmodel ALMOST, waarop REPAS en REACT gebaseerd zijn, worden in dit rapport gedocumenteerd.
Het rapport beschrijft ook de wijze waarop de reverberatie berekend is, die een belangrijk deel van het REACT model is. Er wordt een beschrijving gegeven van twee modules, die achtereenvolgens reverberatie en doels-echo-sterkte berekenen als functie van de tijd. Naderhand wordt voor operationeel gebruik tijd in detectieafstand omgezet.
Tenslotte is er een methode bijgevoegd, om het drempelniveau te bepalen voor verschillende detectiesituaties, te gebruiken in zowel REPAS als REACT. Met deze methode kan ook de detectiekans berekend worden versus detectieafstand. Er worden enkele voorbeelden van detectie-afstandvoorspelling berekend door REPAS en REACT, gepresenteerd.

1 INTRODUCTION

The aim of this report is to describe the following two range prediction models, developed between 1986 and 1990 at FEL-TNO:

REPAS: Range Estimator for Passive sonars and

REACT: Range Estimator for Active sonars.

REPAS and REACT both use the relevant environmental and sonar parameters in their calculations. The ALMOST propagation loss model, which accounts for the environment, takes a central place in both models. ALMOST (Acoustic Loss Model for Operational Studies and Tasks) is the propagation loss model of FEL-TNO, for operational use and study purposes, which was developed between 1980 and 1988. The theoretical basis of ALMOST, a modified ray theory, has been reported by Schippers [1].

REPAS principally consists of an ALMOST propagation loss calculation, followed by a determination of the so-called Figure Of Merite (FOM), which is the maximum tolerable propagation loss for a given passive detection situation.
ALMOST can run either with a so-called incoherent or a coherent sound path summation. The incoherent mode is normally used. The coherent calculation which takes the phase of pressure into account, generally gives an indication of variations in propagation loss in case of small band detection.
The Figure Of Merit (FOM) is calculated in REPAS by means of models for detection threshold and ambient noise. The ambient noise model uses an incorporated data base. In this model modifications are made on sea- and shipping noise with the ALMOST model, to account for sonar parameters and environmental conditions. Also the directivity index is taken into account.
REPAS also calculates the detection probability versus detection range. The detection module can handle broad band detection ("energy detector" case), and frequency line detection (narrow band frequency analysis).

REACT also uses ALMOST, however running the latter in the "active sonar" mode which has no coherent alternative. The results of this mode are propagation loss, arrival time and grazing angle for each important sound path, and for all required ranges. REACT contains, in comparison with REPAS, two extra modules, respectively dealing with:

- the calculation of reverberation and,
- the calculation of target echo level.

A data base of sea surface- and bottom backscattering is incorporated in the REACT model. For the volume scattering strength realistic default input values are available in the model, describing the deep scattering layer.

The reverberation and echo contributions are calculated versus arrival time, by the active sonar mode of ALMOST. Arrival time is afterwards converted to the detection range of active sonars, for operational purposes.

Ambient noise is calculated in the same way as in REPAS.

A detection module for determination of detection threshold and detection probability for a given detection situation, has also been developed for REACT, which treat both CW and FM emissions. Although REACT was principally developed for hull mounted sonars, the model could easily be adapted for active adjunct towed arrays and active sonar buoys. These various active sonar types, each with their own source and receiver directivity patterns, can be chosen by means of a menu.

In the following three chapters the structure and working of ALMOST, REPAS and REACT will be described.

2 ALMOST, THE PROPAGATION LOSS MODEL

ALMOST is the propagation loss model of FEL-TNO, which was developed, for operational use and study purposes, between 1980 and 1988. The model is based on modified ray calculations, see ref. [1].
The model starts with "stylizing" the given Sound Speed Profile (SSP), which is a frequency dependent data reduction process, by means of which also effects of diffraction are described. The result is a stylized SSP of which the number of points has been reduced to a maximum of 13 characteristic ones.
Then the calculation of the propagation loss follows. REPAS uses the propagation loss data per range, by the incoherent or coherent calculation mode. REACT uses propagation loss, travel time and grazing angle data per important sound path, and per range of the target cq. reverberating part of the environment. For this calculation the ALMOST model is used in the active sonar mode.
In the ALMOST model, one can assume on one hand, OMNI reception in the propagation loss calculation, while on the other hand one can execute the calculation for a vertical receiver sensitivity pattern, or a vertical grazing angle interval of reception.
Because the stylizing only requires input of frequency, SSP and bottom depth, in several cases ALMOST can be run with the same stylizing output, which saves computing time.

3 REPAS, THE RANGE PREDICTION MODEL FOR PASSIVE SONARS

For passive sonars the model REPAS can calculate detection range interval(s) with more than a given detection probability P_{det}, or the detection probability curve over a range interval of interest. In the first case a FOM (Figure Of Merit) for the given detection probability (P_{det}=P_{detFOM}) is calculated. The detection module used here, is the same as for the calculation of the detection probability curve.

We start with the passive sonar equation which describes passive detection in general (see Urick [2]):

$$SL - PL - NL = DT \qquad (3.1)\ \text{(passive detection)}$$

with:

- SL = Source Level (=level at 1m in receiver band; dB re μPa.m)
- PL = Propagation Loss (dB)
- NL = Noise Level (self noise and ambient noise; in receiver band; dB re μPa)
- DT = Detection Threshold (dB)

We observe in the above equation that DT is equal to the signal to noise ratio required for detection.

In paragraph 3.1 and 3.2, the dependence of P_{det} on DT will be treated. Subsequently the passive sonar equation 3.1 will be used for the determination of the detection probability (P_{det}) versus range curve.

For the prediction of detection range intervals with a detection probability of more than P_{detFOM}, FOM can be used (Figure Of Merit) defined as:

$$FOM = SL - NL - DTFOM \qquad (3.2)$$

with:

DTFOM = Detection Threshold DT for P_{det}=P_{detFOM}, usually =0.5 (50%)

We easily derive from eq. 3.1 and 3.2:

$$P_{det} > P_{detFOM}$$

when:

$$PL < FOM \tag{3.3}$$

In a graphical representation of eq. (3.3) the so-called FOM-line is drawn in the Propagation Loss (PL) versus range curve. This means that at ranges where PL is smaller than the FOM-value, a detection probability of more than P_{detFOM} is expected (see fig 1, where P_{detFOM} is chosen = 0.5).

The model REPAS starts to calculate PL, the propagation loss versus range (curve) using the ALMOST-model. Incoherent or coherent sound path summation can be chosen, the first being used normally.
Apart from the omni directional calculation, input of a vertical receiver sensitivity pattern, or a vertical grazing angle interval of reception are options in the Propagation Loss (PL) calculation.
FOM is calculated using the incorporated detection module. In general, this module determines DT as a function of P_{det}, P_{fa} (false alarm probability), the integration (processing) time T, and the bandwidth w of the signal. This module is used for the calculation of FOM by setting P_{det}=P_{detFOM}. Using the detection module in another way we can calculate P_{det} directly from DT. With eq. 3.1 we then present P_{det} as a curve versus range, because PL varies with range.
In the detection module we distinguish broad band detection, and narrow band detection, further called line detection. Both cases will be considered successively in the next paragraphs. These cases will result in different mathematical expressions for P_{det}, and thus also for FOM.
Another important term for FOM and P_{det} is NL, the noise level. This will be treated in para 3.3. NL requires the horizontal and vertical directivity pattern of the receiver (if present). This REPAS input has been programmed menu driven, see para 3.4.

3.1 Broad band detection

Broad band signal detection is made by an energy detector, see Van Schooneveld [3]. For the unknown signal in gaussian noise, which generally applies to this passive detection situation, P_{det} is determined by the following equation in an approximation for large bandwidth-time products (wT>>1; see [3], p.82-88):

$$P_{det} = {}^{1}/_{2} \cdot \mathrm{erfc}\left(\frac{\lambda - d}{\sqrt{2}}\right) \qquad (3.4)$$

with:

$d = 10^{(0.1 \cdot DT)} \cdot \sqrt{(wT)}$ (detection index)

$\lambda = \sqrt{2} \cdot \mathrm{erfc}^{-1}(2 \cdot P_{fa})$ (sonar receiver threshold)

$DT = SL - NL - PL$

P_{det} = detection probability

P_{fa} = false alarm probability

w = bandwidth of receiver (Hz)

T = integration time of receiver (s)

This equation for P_{det} yields the P_{det}-curve versus detection range in REPAS, because PL is a function of range.

It is remarked here that P_{fa} is input. For first detection it can be chosen 0.0001, however after a few detections made of the same target, it can be increased up to 0.001 or 0.01, to describe the effect of inzooming by the sonar operator. This will result in a few dB lower DT and higher P_{det}.

For the FOM calculation of REPAS, we calculate DTFOM as DT for the input P_{detFOM} and the input P_{fa}, by inversion of eq. 3.4. Then FOM is calculated with eq. 3.2:

$$FOM = SL - NL - DTFOM \qquad (3.5)$$

with:

$$DTFOM = 5 \cdot {}^{10}\log\left(\frac{d^2}{wT}\right)$$

$$d = \sqrt{2} \cdot [\mathrm{erfc}^{-1}(2 \cdot P_{fa}) - \mathrm{erfc}^{-1}(2 \cdot P_{detFOM})]$$

SL is the source level, calculated by integration of the spectral level over the band of reception w. In this report the noise NL is also taken in the band w. In fact the formulas 3.4 and 3.5 apply to a sonar receiver with noise prewhitening. So for SL we have to integrate the level after prewhitening.

3.2 Line detection

Second, we consider passive detection in a narrow band, of so-called line frequencies emitted by targets. By definition the Source Level (SL) is here determined by the amplitude of the line signal. Just like for broad band, this is the level in the band w.
The noise level (NL) is again the integrated level over the band w.
If a (reasonably stable) line is detected in a small frequency band, we have the case of a (more or less) known signal against gaussian noise. In general it is expected that the signal will fade according to the Rayleigh distribution for the signal amplitude. It is remarked here that small band filtering is in fact correlation with sines and cosines (Fourier transform), so correlation with tonals. This correlation agrees with the assumption of a completely known signal apart from phase and slow Rayleigh amplitude fading (slow means no fading during integration time). The following detection probability (P_{det}) holds for this case (see van Schooneveld [3], p.74-81):

$$P_{det} = P_{fa}^{\,1/(10^{0.1 \cdot DT} \cdot wT+1)} \tag{3.6}$$

with:

$DT = SL - NL - PL$

This yields the detection probability curve of REPAS versus range, because PL is a function of range.
FOM is calculated from 3.2 and inversion of 3.6 for the input $P_{det} = P_{detFOM}$:

$$FOM = SL - NL - DTFOM \tag{3.7}$$

with:

$DTFOM = 10 \cdot {}^{10}\log(\log P_{fa} / \log P_{detFOM} - 1) - 10\log wT$

Typically we find FOM=10.9dB for P_{fa}=0.0001 and P_{detFOM}=0.5.

3.3 Ambient noise calculation

The noise level NL is calculated from the spectral noise. This spectral noise consists of ambient and self noise, both in the receiver beam (if beamforming is applied).
The required spectral ambient noise level is calculated from an incorporated data base with data from Urick [2]. The ambient noise data base has the parameters wind speed, shipping intensity and frequency. Sea- and shipping noise are calculated separately for particular values of these parameters by interpolation in the noise data.
For a vertical receiver pattern, the ambient noise is calculated as being received in this pattern. The ambient noise calculation in this case is based on the supposition that sea noise is generated all over the sea surface, and that shipping noise is generated by distant shipping beyond a distance of 27 km. By calculating with ALMOST, the propagation losses for these wind- and shipping generated sound sources, for an omni- as well as for a vertically directional receiver, both the sea- and shipping noise level from the data base can be adapted for the directional receiver. The result is ambient noise due to sea state and shipping, both adapted to environmental conditions and sonar parameters, while also the Directivity Index DI is taken into account.
Usually DI is calculated. In case of a hull mounted sonar, consisting of circularly grouped staves, the receiver directivity is accounted for by subtracting the horizontal Directivity Index from the total calculated ambient noise value. This DI_{hor} is calculated by integration over the horizontal receiver pattern. For towed arrays however where REPAS, as an approximation, does not take a vertical directivity pattern into account, the 3 dimensional DI is applied (=10logn, with n = number of half wave lengths on receiver aperture).
Finally input is required for the sonar self noise in the beam. The total spectral beam noise level is subsequently calculated as the intensity sum of adapted sea noise, adapted shipping noise, both minus DI, and self noise in the beam.

3.4 Menu driven choice of sonar type

The passive sonar input, consisting of the vertical angle interval or receiver directivity pattern, and the horizontal pattern, is menu driven for easier use. In particular the different calculation methods of these patterns and their application in REPAS for either towed array or HMS, require such menu driven input. The sonar menu has the following form, where the menu number can be chosen in REPAS:

		code:
1.	Towed receiver array	pta
2.	Single hydrophone	shy
3.	Vertical receiver array (for instance: passive buoy)	vla
4.	Hull mounted sonar	hms

See for more details about the calculation of patterns for linear arrays and HMS: paragraph 4.4. As indicated in the menu list REPAS can be used for towed array sonar, buoys, VDS and HMS.

A REPAS plot is shown in fig 1 for the passive mode of a hull mounted sonar, calculated for the sound speed profile of fig 2, a deep winter profile. The heading shows the various REPAS (and ALMOST) parameters, starting with the menu choice. The plot shows the propagation loss curve (PL) with FOM line on one hand, and on the other hand at the bottom the P_{det} curve, versus the passive detection range. It is remarked that according to the definition of FOM, P_{det} equals P_{detFOM} (=0.5 in fig 1) at the range where PL equals FOM.
In addition the main contributing ALMOST propagation modes (see ref [1]) are plotted at 8 different ranges on the range interval. Further the total number of modes for this situation is presented at the top of the cadre. We see in fig 1 that, for the winter profile of fig 2, surface duct propagation is dominant.

4 REACT, THE RANGE PREDICTION MODEL FOR ACTIVE SONARS

The model REACT calculates for active sonars, detection range interval(s) with more than 50% detection probability (P_{det}), or the P_{det}-curve over a range interval of interest. For the determination of the 50% detection range the Minimum Detectable Signal (MDS)-curve is calculated for P_{det}=0.5 (50%). This curve is compared with the calculated target echo level curve. If the echo level is larger than MDS the detection probability is more than 50%.
Active detection is described by the active sonar equation (see Urick [2]):

$$\underbrace{SL - PL_{\substack{to\\target}} + TS - PL_{\substack{from\\target}}}_{TEL} - BGL = DT \qquad (4.1)$$

with:

SL = Source Level of sonar
TS = Target Strength (="nominal secondary" SL of target)
BGL = Background level (noise and reverberation)
DT = Detection Threshold
TEL = Target Echo Level

We observe in the above equation that DT equals the signal to noise ratio required for detection.
In para 4.1, the dependence of P_{det} on DT will be treated. Subsequently the active sonar equation 4.1 will be used for the determination of the detection probability (P_{det}) versus range curve.
For the prediction of detection range intervals with more than 50% detection probability MDS can be used defined as:

$$MDS = BGL + DT50 \qquad (4.2)$$

Like DTFOM in REPAS, ch. 3, DT50 is DT for P_{det}=0.5.
We easily derive from the eq. 4.1 and 4.2:

$$P_{det} > 0.5\ (50\%)$$

when:

$$TEL > MDS \qquad (4.3)$$

Both the TEL- and MDS-curve can be plotted by REACT's plot routine, from which the interval of more than 50% detection probability can be read out (see fig 3). DT50 will be calculated in para 4.1.

In eq. 4.1 we see propagation loss (PL) to and from the target. In the same way there is PL to and from any reverberating part of the environment, consisting of sea surface, volume (Deep Scattering Layer DSL) and bottom. For DSL the input is 9 layers. PL is calculated for these mechanisms, and for the two ways separately, applying ALMOST. REACT applies ALMOST in the so-called active sonar mode. The stylizing of ALMOST is used in the same way as for REPAS, but in REACT always for one frequency per calculation. The ALMOST propagation loss calculation yields here per important propagation path: PL, arrival time, and grazing angle at target, for all target ranges cq. ranges for the reverberation (RL) calculation. For respectively target and environment (reverberation), all combinations of paths "to" and "from" are made, in respectively the TEL- and the RL calculation. REACT calculates "quasi monostatic", which means: source and receiver at same geographic position with option of different depths. Also the vertical patterns of reception and emission may be different. In contrast to REPAS, a simple vertical angle interval for source or receiver is not allowed in REACT because the prediction may become poor if the effects of sidelobes are neglected, which will be shown further in this chapter, in para 4.5. The calculations are made versus the arrival time which is the sum over a path "to" and a path "from". In general there is backscattering with different angles of incidence and scattering. In particular for the reverberation calculation this has to be taken into account. Further, there is for REACT no alternative coherent calculation mode, since coherence will be lost by the scattering mechanism.

A few remarks still have to be made about the reverberation calculation. For surface scattering, the distributed secondary sound sources are placed at a depth of 0.1m, because ALMOST does not accept an input of 0m. (In general the acoustic pressure will be zero at the sea surface.) The so-called surface decoupling loss has been omitted in the active sonar mode of ALMOST to get a realistic description. Moreover as there are allways two nearly congruent rays: with and without reflection, the (linear) scattering strength has been divided by 2, which is also of application for the bottom scattering data.

Finally there are some remarks about the effective surface- cq. volume part to which the scattering data are applied. Although reverberation is, in fact, the convolution of distributed scatterers with the emitted pulse shape, this complicated calculation is approximated by taking parts of size cT/2 in the direction of the ray paths. However, the angle of incidence and the division of the environment in range intervals, also determine the horizontal size of the scattering part, which is accounted for in the reverberation calculation.

The single paths from source to receiver, SRP- and BSP mode propagation in ALMOST terms (see ref. [1]), are calculated versus time, by application of the active sonar mode of ALMOST. The well-known "fathometer effect" is included in this type of detection background.

These single paths are, in many sonars, received in sidelobes, which results in suppression of the effect. For towed receiver arrays the REACT approximation does not apply a vertical receiver pattern. However for steering angles which are not broadside the sidelobe level in the vertical direction is accounted for.

For a single target, one emitted pulse can result in several echoes splitted in time. REACT supposes a number of identical targets over an input range interval (maximum 100 targets). TEL is calculated by taking at each time bin, the strongest of the echo levels of all these targets.

The reverberation is calculated for the same range interval. This part of the environment (sea surface, -volume and -bottom) is divided in a number of range intervals (max. 100) each producing (back)scattered intensity. This number of ranges is taken equal to the number of target ranges.

Afterwards the arrival time scale is replaced by a corresponding detection range scale in the operational plot.

The remainder of this paragraph will concentrate on modeling of detection threshold and doppler, followed by general remarks about the backscattering data base used for the reverberation modeling. After this whole basic description of REACT, the menu driven input for different sonar types will be described, and some examples of REACT predictions will be given.

4.1 Detection threshold

The modeling of Detection Threshold DT depends on the statistics of echo signal and background, and the type of sonar receiver. This problem can also be formulated as calculating the detection probability P_{det} as a function of DT, which is in fact the signal to noise ratio.
In a modern active sonar the echo signal is correlated with the known emitted signal shape. This is the detection case of a completely known signal against a background of noise and reverberation. The echo signal will possess fading. This is mathematically the same detection case as for passive line detection (para 3.2).
To calculate DT for the background of noise plus reverberation, first the two limit cases will be considered: background of noise only, and of reverberation only. Finally the general mixed background will be considered.
The formula of P_{det}, the detection probability for the case of a known signal with slow Rayleigh fading in gaussian noise is as follows (see Van Schooneveld [3], p.74-81, and also eq. 3.6):

$$P_{det} = P_{fa}^{\;1/(10^{0.1 \cdot DT}+1)} \tag{4.4}$$

with:

DT= TEL - NL+10*^{10}log(wT)
NL= noise level in band w
w = bandwidth of receiver (Hz)
T = integration time of receiver (s) = pulse length

The only difference with eq. 3.6 is that the wT product is larger than 1 here. NL is calculated, like in REPAS, accounting for sonar self noise as well as ambient noise level in the vertical receiver pattern (input: wind speed, shipping intensity; see para 3.3).
Because the ambient noise level is calculated as the omni directional level received in the vertical receiver pattern of the sonar (see REPAS para 3.2), this value is subsequently decreased with the horizontal Directivity Index DI. The latter is calculated by integration over the horizontal receiver pattern. This method is followed for hull mounted sonars, consisting of staves, circularly grouped, and for active sonar buoys. However an exception is made for the towed receiver array (with active adjunct). This has no vertical pattern in the REACT approximation, so DI is calculated here based on the number of half wave lengths n on the array length (DI=10logn).

Subsequently DI is subtracted from sea- and shipping noise level, and then combined with the sonar beam self noise.
If the above known signal must be detected in a background of reverberation (RL), possessing a Rayleigh distribution, we calculate in a good approximation the same formula for P_{det} however without background reduction of wT like gaussian noise in 4.4:

$$P_{det} = P_{fa}^{\,1/(10^{0.1 \cdot DT}+1)} \qquad (4.5)$$

with:
DT = TEL - RL
RL = reverberation level

The matched filter receiver causes time compression of the emitted pulse signal from T down to a time 1/w (see ref. [3]). This results in a reduction of RL with 10logwT.
For the general detection case of a background of noise plus reverberation the following formulation for P_{det} is adopted, in agreement with the above limiting cases (eq. 4.4 and 4.5):

$$P_{det} = P_{fa}^{\,1/(10^{0.1 \cdot DT}+1)} \qquad (4.6)$$

with:
DT = TEL - BGL
BGL = intensity summation of RL and NL-10logwT

In the following this expression for P_{det} will be applied to the two main pulse types for active, matched filter sonars:
FM: Frequency Modulated pulse and
CW: Continuous Wave pulse.
In the latter case (CW) w is relatively small, w=1/T. So in the CW case, the product wT in eq. 4.6 equals 1. Generally, a doppler shift in frequency, of the received signal is caused by sonar and target speed. For each frequency interval w of the whole reception band for doppler shifted echoes, a separate matched filter is needed. This receiver type is usually indicated as a "doppler filter bank" receiver. It makes in fact the Fourrier transformation of the signal in the entire

receiver band. Of course there is no time compression in the CW case. So, compared with FM, the resolution of the active detection ranges found with CW, is usually much worse.
It must be remarked that also in FM sonar receivers often a few doppler shifted replicas are used for the optimum matched filter output. REACT supposes such optimized receivers.
The MDS curve is calculated from DT50, see eq. 4.2. DT50 follows from inversion of eq. 4.6, like 3.6, of course for both CW and FM (CW is in fact FM with wT=1):

$$DT50 = 10 \cdot {}^{10}\log(\log P_{fa}/\log P_{det} - 1) \qquad (4.7)$$

with:

$P_{det} = 0.5$

Typically we find DT50=10.9dB for Pfa=0.0001.

There are however older CW sonars which do not use a doppler filter bank. The reception band for the CW mode is designed such wide that usually all possible doppler shifted target echoes are received. This relatively simple detector type can be described as the energy detector (see [3], p.82-88, and also eq. 3.4):

$$P_{det} = {}^1/_2 \cdot \mathrm{erfc}\left(\frac{\lambda - d}{\sqrt{2}}\right) \qquad (4.8)$$

with:

$d = 10^{(0.1 \cdot DT)}$ (detection index)

$\lambda = \sqrt{2} \cdot \mathrm{erfc}^{-1}(2 \cdot P_{fa})$ (sonar receiver threshold)

$DT = TEL - BGL$

BGL = intensity sum of RL (without time compression) and NL - $5 {}^{10}\log wT$

In REACT this type of sonar has been called "CW-energy" detection. MDS follows in this case again from 4.2, with DT50 calculated by inversion of 4.8 (see also 3.5):

$$DT50 = 10 \cdot {}^{10}\log\lambda \qquad (4.9)$$

$$\lambda = \sqrt{2} \cdot \mathrm{erfc}^{-1}(2 \cdot P_{fa})$$

where P_{det}=0.5 has already been substituted.

4.2 Doppler effects

It is possible, that a target echo possesses a doppler-shift on the frequency scale compared to the reverberation, due to the target speed. If target echo and reverberation do not fall in the same doppler-filter band (width w), detection has to be made against a noise background NL only. In particular for CW, with small w values, this results in a more favourable detection situation.

For shifts smaller than w, a decreased reverberation level is taken into account based on interpolation.

Also the speed of the sonar vessel is of importance for RL, causing the following complicated effect. Reverberation contributons from different horizontal directions possess different doppler shifts. Much of this reverberation is received in sidelobes. Some reverberation, mostly from sidelobes, may fall in the doppler band of the main target echo ("main" in case of echo splitting). This effect has been modeled in REACT, by the calculation of a horizontal angle interval for which the reverberation has a doppler shift comparable to that of the target echo. The average direction together with the effective width of this horizontal angle interval are calculated. The reverberation contribution is proportional to this width.

In REACT, doppler shifts of reverberation and single paths are calculated relative to the frequency shift of the main target echo. The latter will in general be shifted in the absolute sense (Δf) if there is a target speed component in the main beam (target) direction. REACT calculates the doppler-shift relative to the target echo Δf_{rel} from the absolute doppler shift Δf, for each reverberation contribution.

The absolute doppler shift of the target echo is determined by the projection of sonar and target speed on the vertically inclined sound paths. For the absolute doppler shift of reverberation the "target speed" must be taken zero:

$$\Delta f = f \cdot (V_{son} \cdot \cos \Phi - V_{tgt}) \cdot (\cos \theta_{to} + \cos \theta_{frm}) / c \qquad (4.10)$$

with:

Δf = Doppler frequency shift

f = frequency

V_{son} = speed of sonar ship

V_{tgt} = speed of target in target direction (bearing; >0=leaving; =0 for RL)

Φ = bearing angle of target (horizontal)

c = sound speed

θ_{to} = grazing angle of path to target (vertical)

θ_{frm} = grazing angle of path from target

The single paths (fathometer effect) possess no absolute doppler shift, as source and receiver have the same speed, and the reflecting horizontal bottom is right below source and receiver.

It should finally be remarked that for moving targets no or very little advantage can be achieved by using doppler-shifts in case of FM-pulses. This is due to the relatively large bandwidth w of the frequency sweep of such pulses.

4.3 Scattering data

REACT requires scattering data for the surfaces (sea surface cq. -bottom) and the volume. For the surfaces the usually different angles of incidence and scattering in REACT, as we have seen above, are parameters for the scattering strength. For surfaces the target strength per m^2 is required, and for the volume the target strength per m^3, the latter independent of the angles.
Such detailed data for the surfaces are not available in the literature. It should be noted that bottom type and frequency are also parameters for bottom scattering. In the same way wind speed and frequency are also parameters for sea surface scattering.
In the literature only data for real backscattering are available, in stead of scattering into various angles. So these data have to be adapted for use in REACT, to handle the different angles of incidence and scattering. This adaptation method will be treated below. First however some remarks about the data from the literature.
A database for sea surface- and bottom backscattering strength as a function of grazing angle and frequency has been constructed. In fact the sea surface- and bottom backscattering curves (versus angle) have been read out in their characteristic points, and added to the data base.

Sea surface data have been taken from Urick [2]. Arrays of backscattering curves versus angle are given with wind speed as parameter. The observed frequency dependence in these data is not very large. Therefore, a data set representing these curves is composed for each of the following three adjacent frequency bands:

1) 0.02 - 2.5 kHz
2) 2.5 - 13 kHz
3) 13 - 31 kHz,

thus covering a large frequency range of application: 20 Hz to 31 kHz. This means that no frequency interpolation is made here in REACT.

Bottom backscattering curves for bottoms with different roughness (-type), are given in Urick [2] in a similar way. The measure of bottom roughness has been linked to the MGS-number, already used in ALMOST (see [1]), which could only be done in a global approximate way (the MGS number is principally used to describe the forward bottom reflection loss). The obtained arrays of backscattering curves versus angle with the MGS-number as the adopted parameter, are used in a similar way as the sea surface backscattering data. The frequency intervals of application of these bottom data are also large, so for practical reasons the same frequency bands have been chosen as for the sea surface.

The calculation of the backscattering for the given wind speed cq. MGS-number, from the above constructed data base is performed by calculation of an interpolated curve (versus angle) for the required parameter values. The data sub set for the relevant frequency band is applied here.

The backscattering data (for equal angles of incidence and scattering) are adapted in REACT to determine the scattering in any direction, which is required for the calculation of the reverberation level. This is achieved by making use of Lambert's scattering law for angular intensity distribution (see Urick [2]):

$$SS\ (\theta_i,\theta_s) = SS\ (\theta_i) \cdot \frac{\sin \theta_s}{\sin \theta_i} \qquad (4.11)$$

with:

SS = Scattering Strength of sea surface cq -bottom, per m^2
θ_i = incident grazing angle (vertical)
θ_s = angle of scattering

The database can easily be updated if better data become available. Because of lack of scattering strength data for small angles, extrapolations have been made according to the behaviour of high frequency data in ref [2]. With these data REACT's results compare well with measurements in literature.

The volume backscattering data, given as a function of depth, form a default input for a Deep Scattering Layer (DSL). The volume scattering values are only 9 default figures for the 9 sub layers in REACT, which can be changed if required.
The data taken from Urick [2], are principally independent of grazing angle. A frequency dependent trend of the mean scattering level of the DSL, as given by Urick [2], is also implemented in REACT. This trend forms a good default description of the DSL, but it can simply be deleted for special cases.
The depth, thickness and scattering level of the DSL can easily be adapted in REACT by changing the sub layers of constant scattering strength: For instance a depth change of the whole DSL may be important for a better description of the day and night situation.

4.4 Menu driven choice of sonar type

REACT, at this stage, can be run for HMS, active adjunct and active sonar buoys. It is of great importance that the input source and receiver directivity patterns are chosen in the right way. There are two possibilities, calculation of the patterns from the geometry of (in most cases) distributed projectors and hydrophones, or reading the patterns from a file. The menu shown next, particularly assists when the option is chosen of calculating the patterns. The menu also plays a role in the calculation of the Directivity Index DI and the sidelobe level at which the single paths (fathometer-effect) are received. This means that the input menu number is used in all cases of REACT calculations.

The calculation of the patterns is done for linear source and receiver arrays in an exact way, however supposing no shading.

HMS sonars have vertical staves which are grouped in a (horizontal) circle. Supposing that a half circle of staves emits cq. receives, the horizontal pattern is calculated by using a linear replacing array coinciding with the diameter of the circle, and filled with elements at a selectable spacing ("input spacing"), which is usually taken as half a wave length. The beam shape is always calculated for the broadside case. This linear replacing array yields in broadside two symmetric beams of which one is deleted in the calculation, because such a second beam is not present in the HMS beam forming. In order to calculate realistic patterns a selectable minimum sidelobe level is taken into account in all pattern calculations used in REACT (and REPAS).

The vertical HMS pattern is calculated starting with the pattern of one stave. Linearly grouped elements are assumed, at equal "input spacing", in agreement with the geometry of a HMS (stave). Subsequently this pattern is multiplied by the vertical pattern of the (emitting cq. receiving) horizontal half circle. This second pattern is again calculated using a replacing linear array. This linear array is chosen half the length of the circle diameter, horizontally, in the beam direction, with the elements at the selected "input spacing", and steered in endfire direction.

In case that the sonar does not use exactly half the number of staves for the beamforming, the supposed acoustic diameter can be chosen somewhat smaller. The in this way calculated HMS patterns appear to agree very well with data of the manufacturer. The advantage of pattern calculation is that frequency changes are automatically taken into account, given the geometry.

The sonar menu looks as follows, where the menu number can be chosen in REACT:

code:

1.	Towed receiver array/ vertical source array (for instance: ATAS, active adjunct)	atd
2.	Towed receiver array/ single source	atm
3.	Vertical receiver array/ vertical source array (for instance: active buoy)	bvd
4.	Vertical receiver array/ single source	bvm
5.	HMS/ omni- cq. TRDT emission	hms
6.	HMS/ single beam emission	hmb

It is remarked that for a HMS used in the so-called TRDT mode, the prediction has to be made using the same menu (hms) as for OMNI, however with the appropriate higher source level.
It is possible to expand the menu if required.

4.5 Examples of REACT calculations

Some examples of REACT plots are shown in fig 3 to 8, for an active adjunct low frequency sonar, an ATAS sonar (Active Towed Array Sonar), and a hull mounted sonar for which the REACT model was originally developed. The Sound Speed Profile (SSP) given in fig 2, is a typical deep winter SSP. Sonar and target are situated within the 90m deep Surface Duct. As indicated in the heading of the plots the full array geometries of the sonars chosen have been taken into account.

Successively, the sonar menu choice and all REACT parameters of sonar and environment, are given in the heading of the REACT plots. The curves are plotted versus range, and echo levels are compared with MDS. All plots are of the so-called operational type except for fig 5 which is of the so-called theoretical type. Here the echo splitting in time is presented explicitely using different symbols for the target ranges. The maximum number of target ranges is only 20, in stead of 100 for the operational plots. In the theoretical plot the reverberation level is plotted separately, also indicating the main contributing reverberation mechanism(s):

S = surface;
B = bottom
L = DSL.

For the operational plots, P_{det} is presented as a function of range as well. It is remarked that P_{det} equals 0.5 at the range where echo level and MDS are equal.

The importance of realistic beam patterns in stead of approximations by rectangular beam shapes is illustrated by fig 7 and 8. In fig 8 a rectangular horizontal beam shape without sidelobes is used, with a realistic width of 11 degrees for the HMS sonar. Compared to fig 7, using the complete horizontal pattern, a big difference in reverberation level is shown, even for the high target speed of 6m/s. A positive speed value means that the target moves away from the sonar ship, in the beam direction, with the given speed, while a negative value means approaching. In fig 7, doppler shifted reverberation is received in sidelobes only, but this level appears to be of importance in the REACT prediction. In fig 8 this level is not present due to the rectangular beam shape with no sidelobes, resulting in a too optimistic prediction. It is remarked that a change in Target Strength TS simply results in a vertical shift of the Target Echo Level curve.

In fig 10 to 13 the REACT calculations of fig 5 to 8 have been repeated for a summer case, for which the SSP is given in fig 8. We see that the high reverberation contribution for the winter case (fig 5 to 8), due to surface reverberation, is not present in the summer case. Also the echo levels are much lower due to bad propagation conditions (no surface duct). The small maximum in fig 11 at about 5km represents bottom echoes from very close targets as shown in the theoretical plot (fig 10). In fig 12 and 13 this feature is not present anymore because at the target speed of 6m/s there is a large doppler shift difference between direct and bottom reflected paths, due to the steep grazing angles of the latter. This is contrary to the case with target speed 0m/s of fig 10 and 11, where the doppler shift difference between direct and bottom paths is such that the echoes fall partly in the same doppler band, causing the small maximum at about 5km.

5 CONCLUSIONS

A complete description of the passive and active sonar range prediction models REPAS and REACT has been presented in this report, together with some examples, for HMS and active adjunct sonars, in two different seasons.

The REPAS model uses both propagation loss, determined by the already tested ALMOST model, and a detection module, to calculate the final passive sonar range prediction.

The REACT model also uses the detection module, but calculates in addition the reverberation level with the aid of a special calculation mode of ALMOST. ALMOST is used here for the calculation of propagation losses and arrival times for separate sound paths. The method of calculation is also applied to the calculation of the splitted target echo level. In addition doppler effects in all sound paths are taken into account for the reverberation as well as for the echo. An incorporated data base of environmental backscattering data is used for the reverberation calculation.

Both models further make use of an ambient noise model, using the receiver beam pattern and an incorporated ambient noise data base.

The menu driven input for both REPAS and REACT allows for operational use at sea and facilitates their use in studies. The menu takes care of the specific sonar input, which is rather complicated, due to the directivity patterns resulting from the sonar geometry. In this way the input of false or unrealistic parameters is avoided.

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(author)

FIGURES

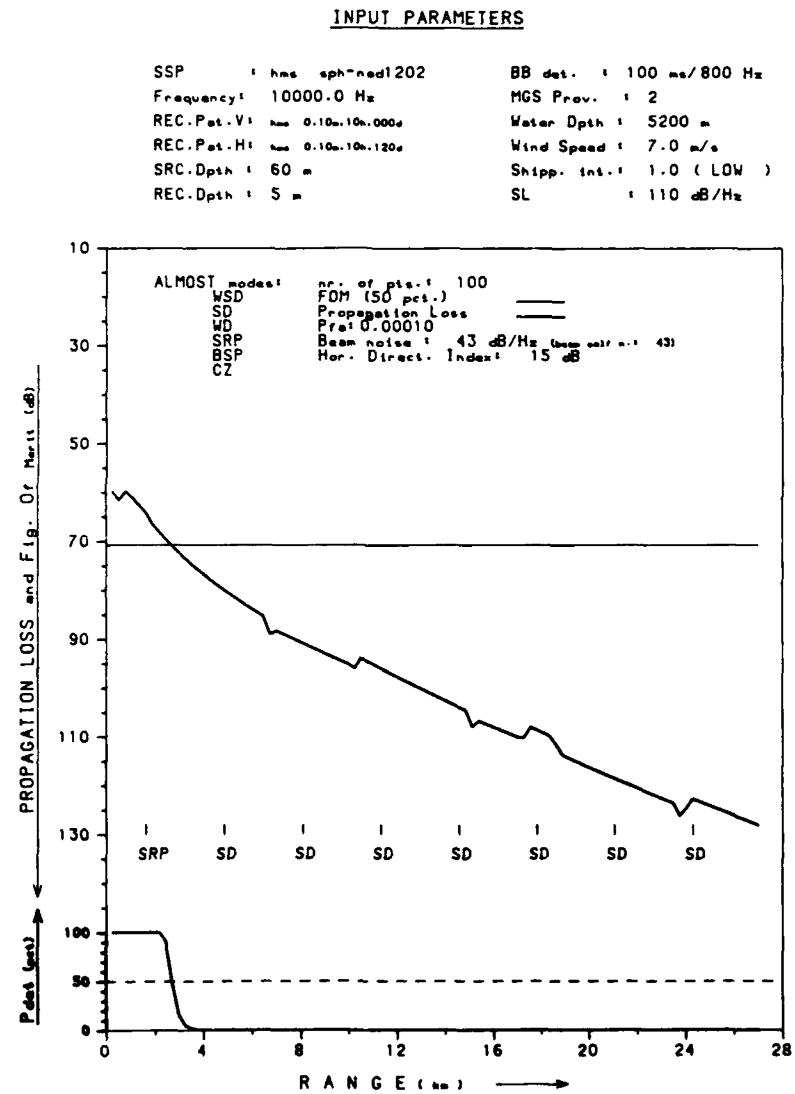
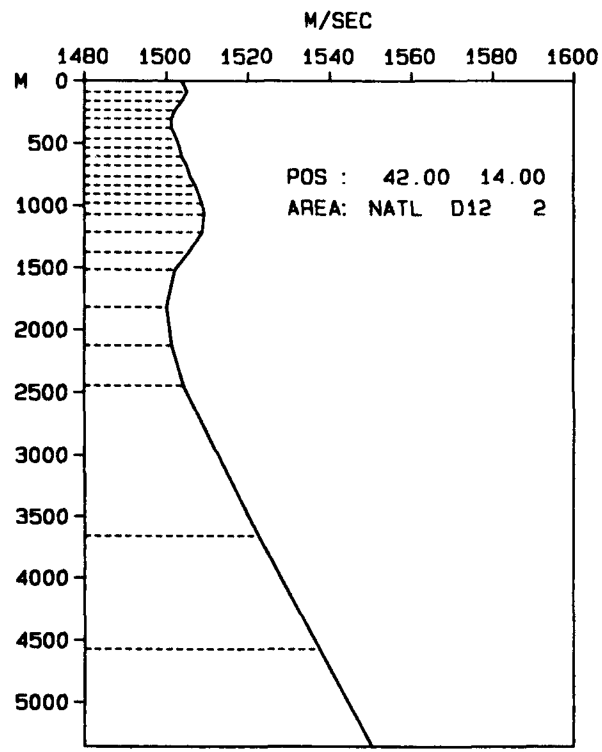


Fig. 1: **REPAS, using ALMOST.**

PROFILE PLOT



PROFILE TABLE

DEPTH (M)	SOUND SPEED (M/SEC)
0	1503.58
91.4	1505.10
152.4	1503.88
228.6	1502.05
304.8	1501.14
381.0	1501.44
457.2	1502.36
533.4	1503.27
609.6	1503.88
685.8	1505.10
762.0	1505.71
838.2	1506.93
914.4	1507.85
990.6	1508.76
1066.8	1509.06
1219.2	1508.76
1371.6	1505.41
1524.0	1502.05
1828.8	1499.92
2133.6	1501.44
2438.4	1504.19
3657.6	1522.48
4572.0	1537.41
5486.4	1552.65

Fig. 2: Historical sound speed profile of winter type.

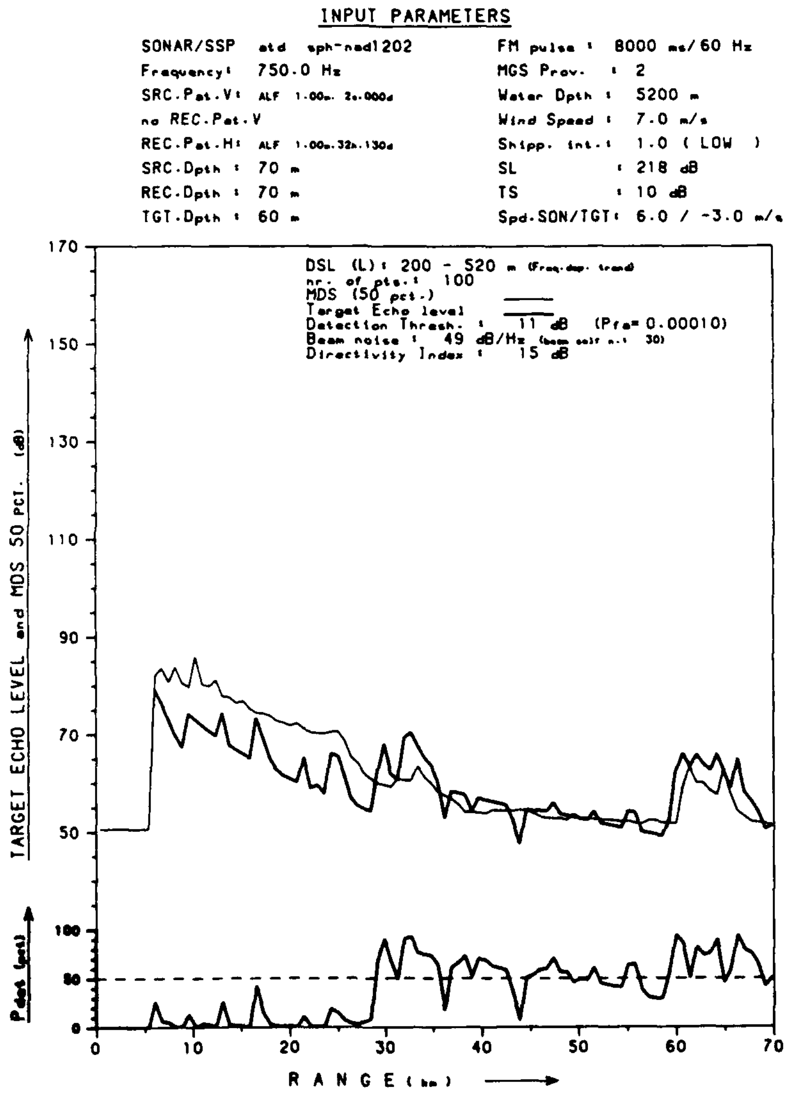


Fig. 3: **REACT, using ALMOST; towed array with active adjunct; winter case.**

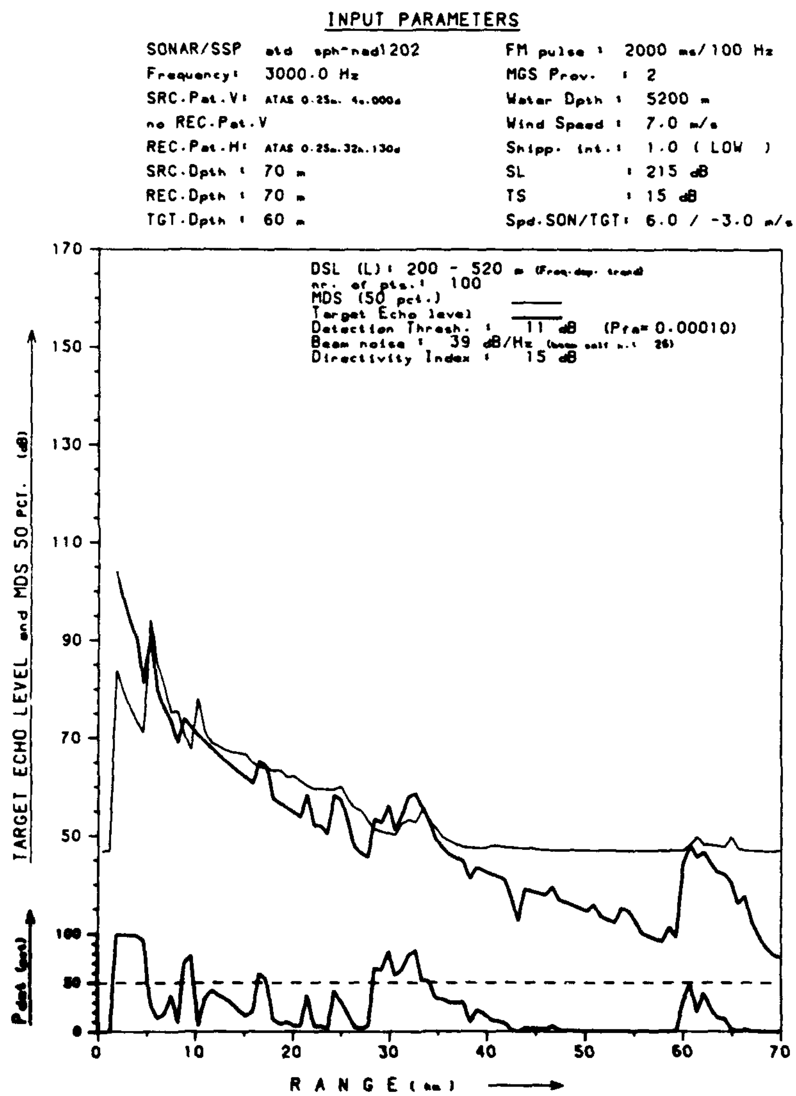


Fig. 4: **REACT, using ALMOST; towed array with active adjunct; winter case.**

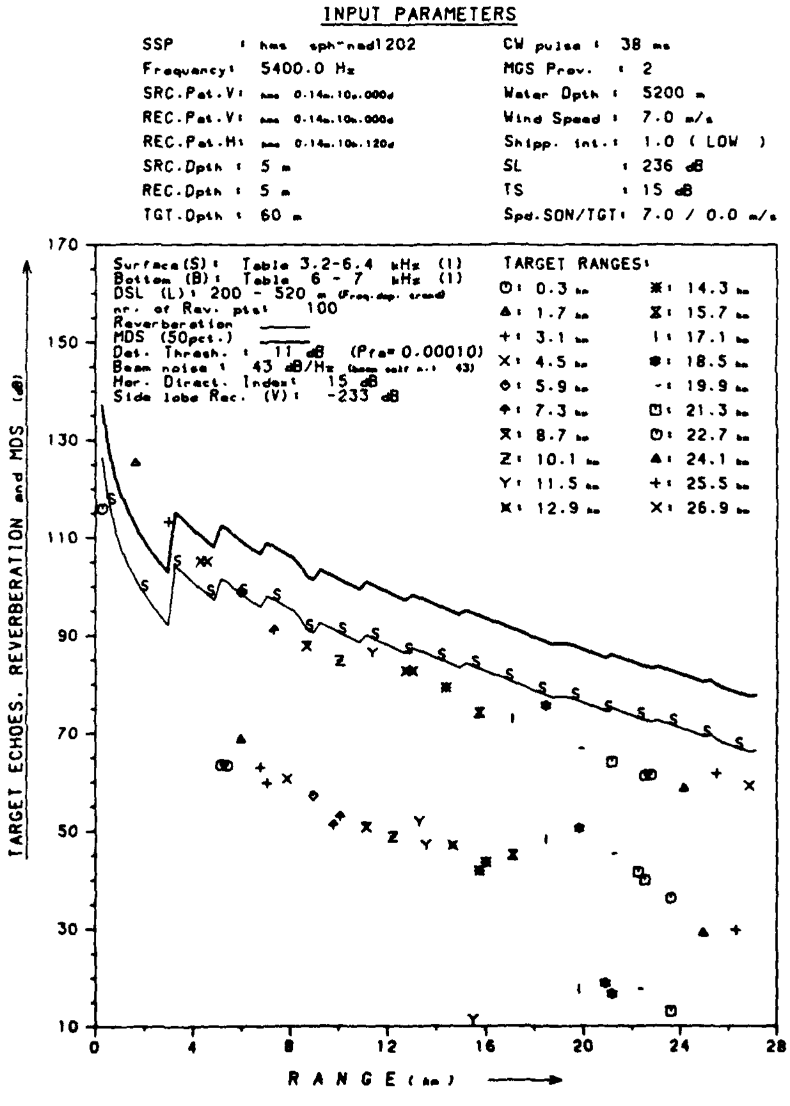


Fig. 5: **Theoretical version of REACT (using ALMOST); HMS-sonar; no doppler/winter case**

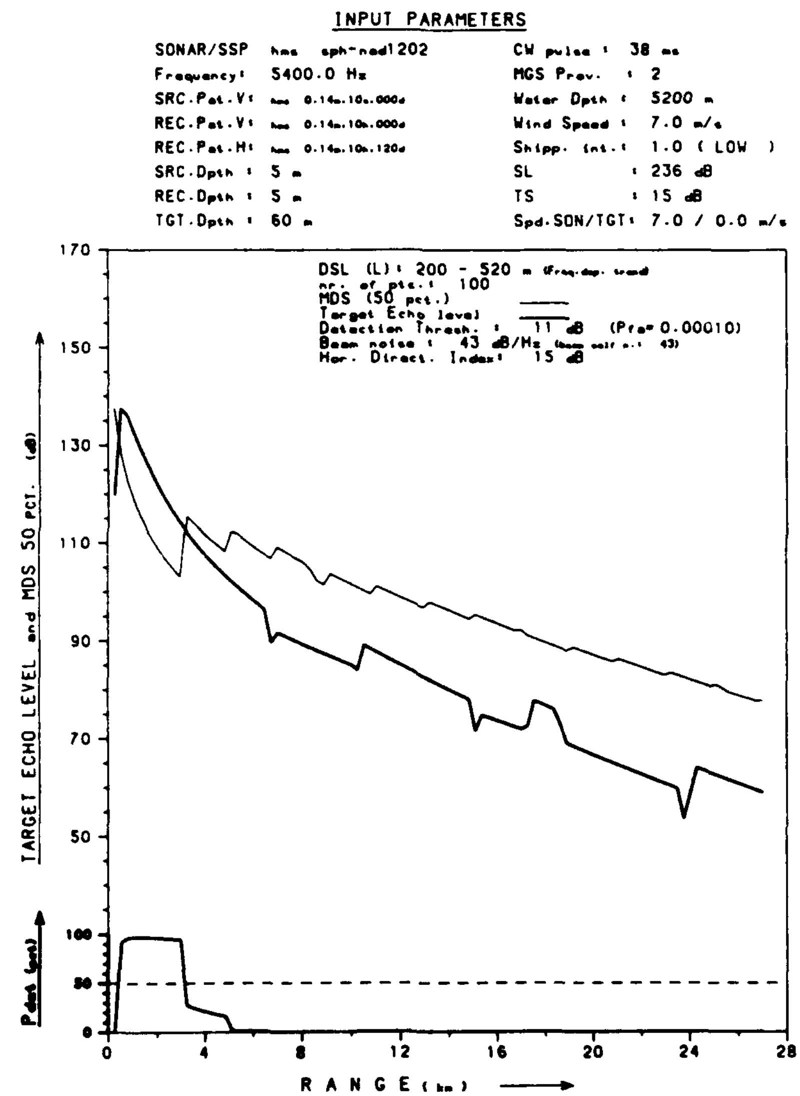


Fig. 6: REACT, using ALMOST; HMS; no doppler/ winter case.

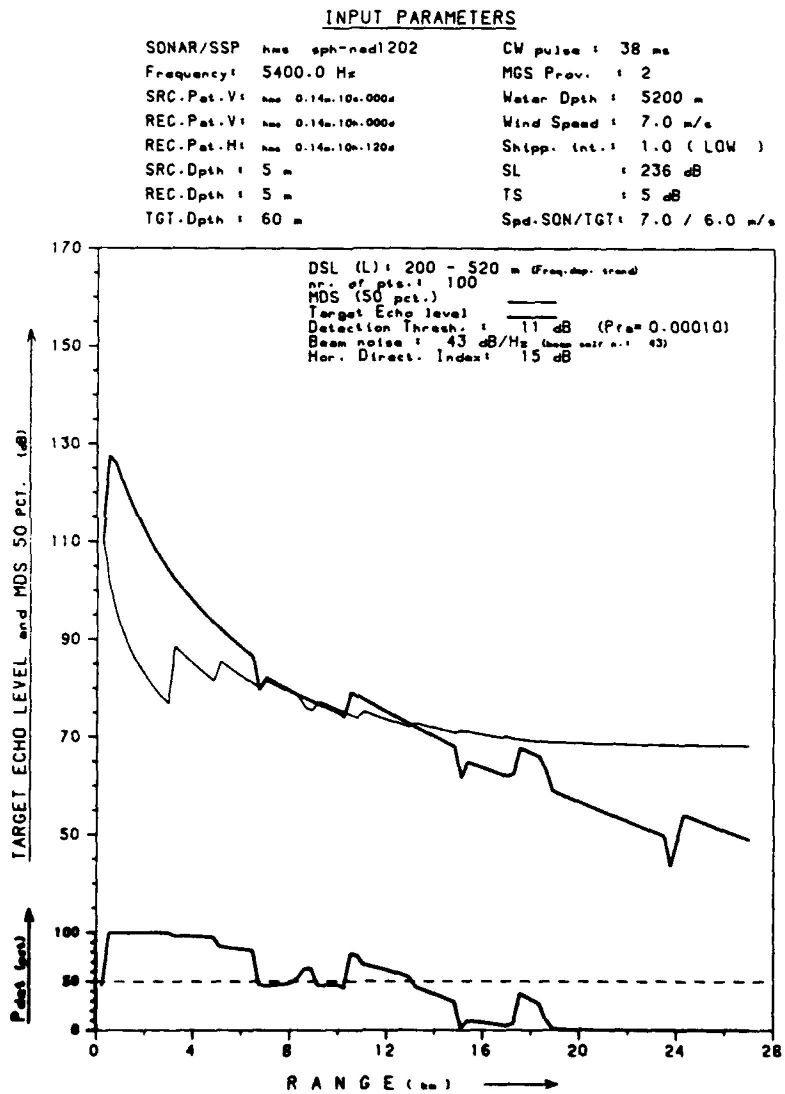


Fig. 7: **REACT, using ALMOST; HMS; doppler/ winter case.**

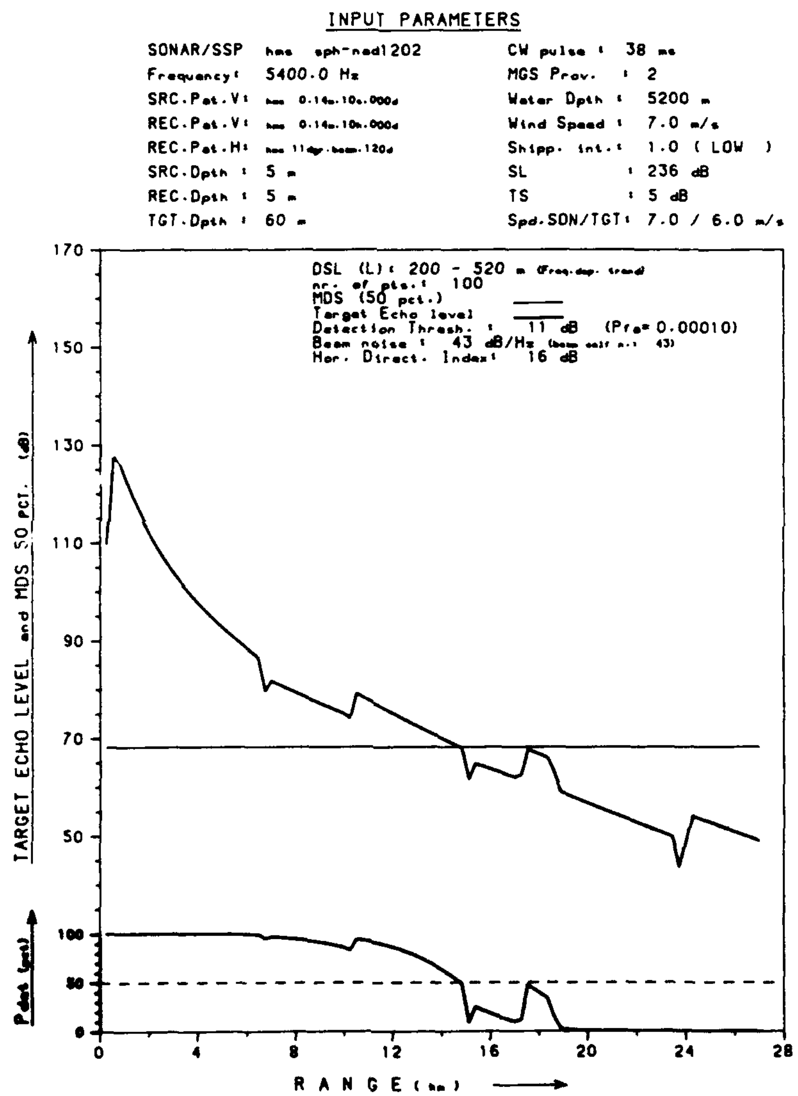
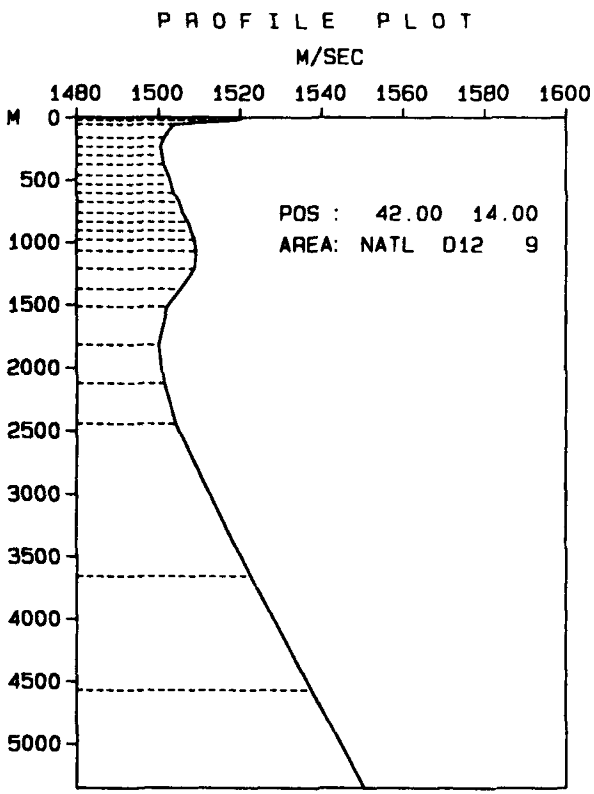


Fig. 8: **REACT, using ALMOST; HMS with rectangular beam shape, without sidelobes; doppler/ winter case.**



P R O F I L E   T A B L E

DEPTH (M)	SOUND SPEED (M/SEC)
.0	1520.65
18.3	1519.73
61.0	1503.88
152.4	1501.44
228.6	1500.53
304.8	1500.84
381.0	1501.44
457.2	1502.36
533.4	1503.27
609.6	1503.88
685.8	1505.10
762.0	1505.71
838.2	1506.93
914.4	1507.85
990.6	1508.76
1066.8	1509.06
1219.2	1508.76
1371.6	1505.41
1524.0	1502.05
1828.8	1499.92
2133.6	1501.44
2438.4	1504.19
3657.6	1522.48
4572.0	1537.41

Fig. 9: Historical sound speed profile of summer type.

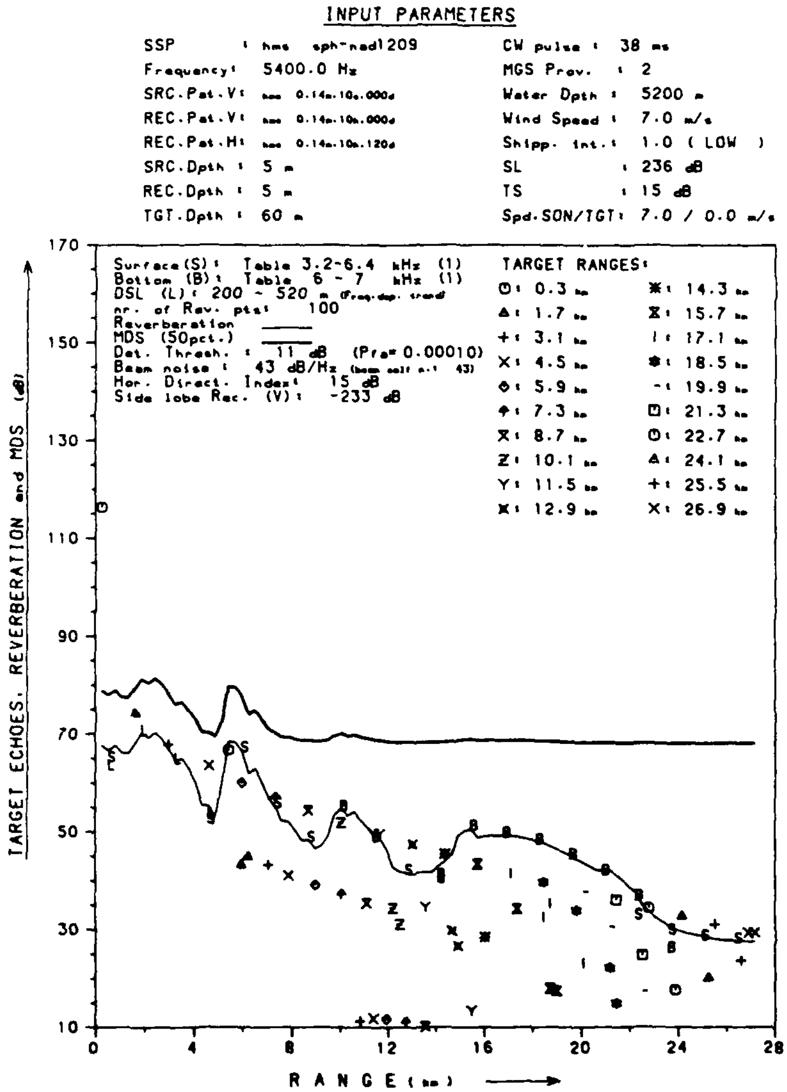


Fig. 10: Theoretical version of REACT (using ALMOST); HMS; no doppler/ summer case.

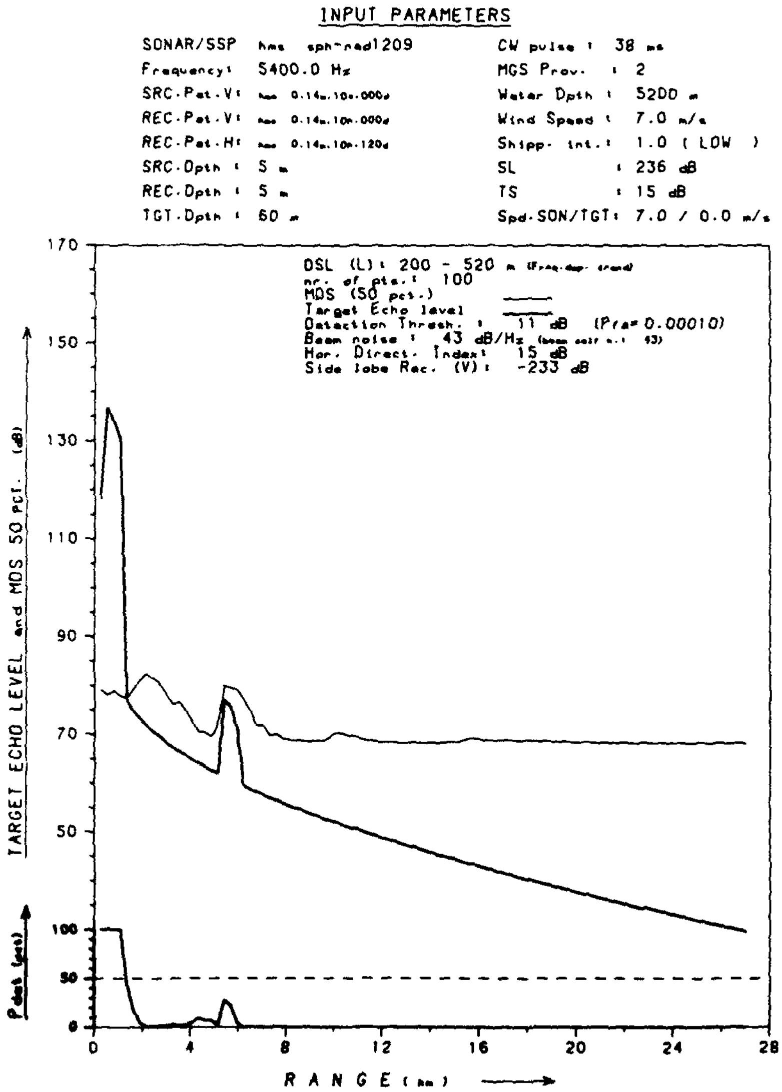


Fig. 11: REACT, using ALMOST; HMS; no doppler/ summer case.

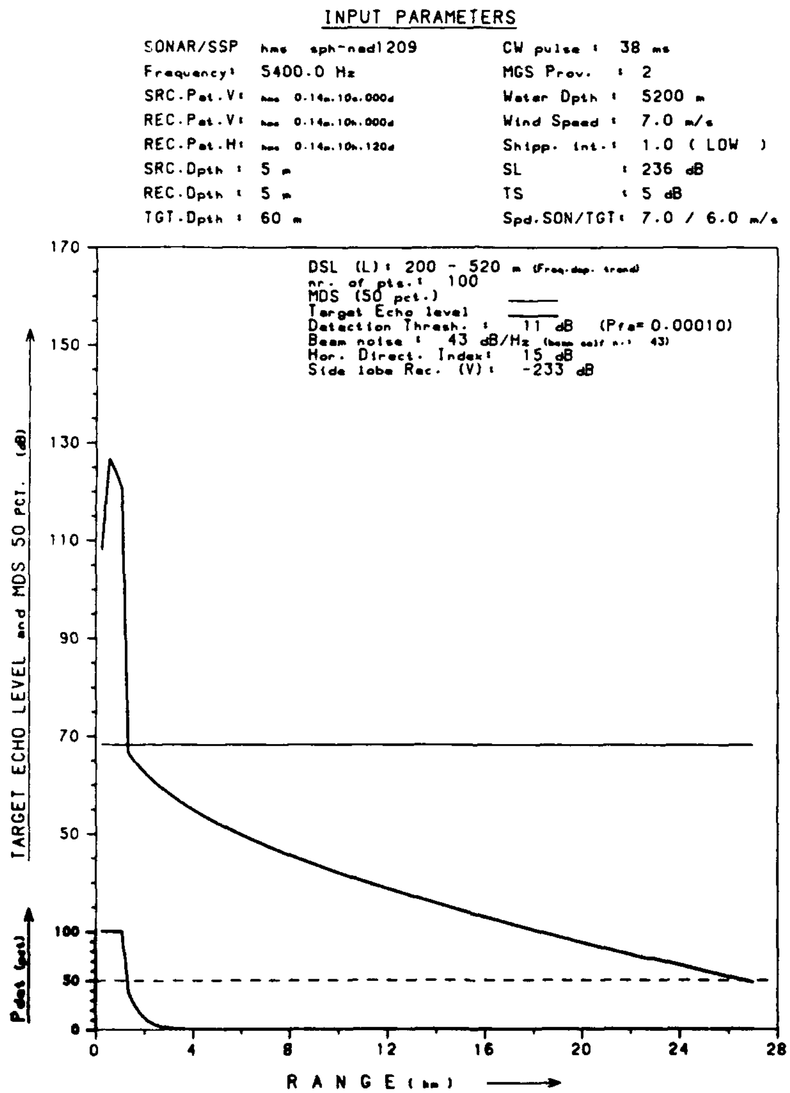


Fig. 12: **REACT, using ALMOST; HMS; doppler/ summer case.**

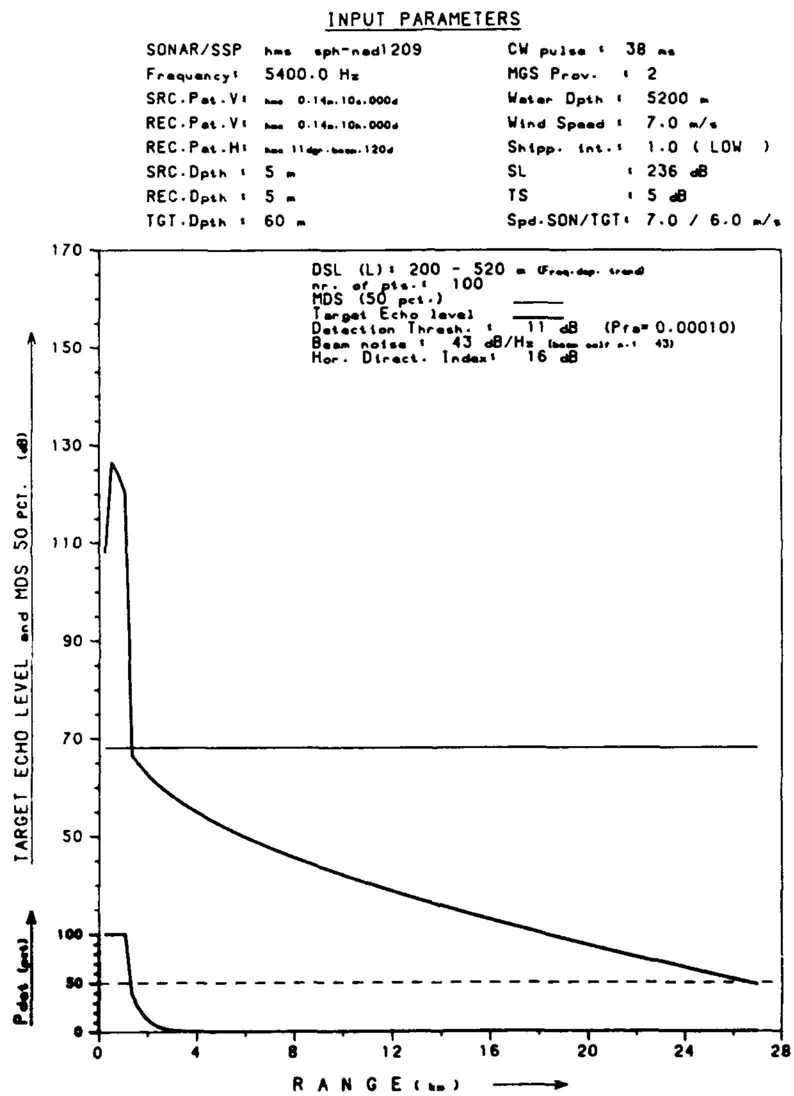


Fig. 13: **REACT, using ALMOST; HMS with rectangular beam shape, without sidelobes; doppler/ summer case.**

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THE RANGE PREDICTION MODELS REPAS AND REACT FOR PASSIVE AND ACTIVE SONARS RESPECTIVELY, HAVE BEEN DEVELOPED AT FEL-TNO BETWEEN 1986 AND 1990 . THESE MODELS AND THE PROPAGATION LOSS MODEL ALMOST ON WHICH REPAS AND REACT ARE BASED, ARE DOCUMENTED IN THIS REPORT.
THE REPORT DESCRIBES ALSO THE WAY IN WHICH THE REVERBERATION IS CALCULATED, WHICH IS AN IMPORTANT PART OF THE REACT-MODEL. A DESCRIPTION IS GIVEN OF TWO MODULES, WHICH CALCULATE REVERBERATION AND TARGET ECHO LEVEL AS A FUNCTION OF TIME RESPECTIVELY. AFTERWARDS TIME IS CONVERTED TO DETECTION RANGE FOR OPERATIONAL USE.
FINALLY A METHOD HAS ALSO BEEN INCLUDED, FOR THE DETERMINATION OF THE THRESHOLD LEVEL FOR VARIOUS DETECTION SITUATIONS, USED IN REPAS AS WELL AS REACT. WITH THIS METHOD ALSO THE DETECTION PROBABILITY CAN BE CALCULATED VERSUS DETECTION RANGE. SOME EXAMPLES OF DETECTION RANGE PREDICTION CALCULATED BY REPAS AND REACT ARE PRESENTED.

16. DESCRIPTORS	**IDENTIFIERS**
PASSIVE SONAR	ACTIVE SONAR
MODELS	ALMOST
UNDERWATER SOUND PROPAGATION	
UNDERWATER SOUND SCATTERING	
UNDERWATER SOUND REVERBERATION	
UNDERWATER ACOUSTICS	

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